High Energy Physics at LBNL:

Status and Outlook

March 2005

Executive Summary

The High Energy Physics program at LBNL, comprising the entirety of the Physics Division and a portion of the Accelerator and Fusion Research Division (AFRD), brings a unique combination of university and laboratory resources to the international high energy physics program. This document provides a brief summary of the current research program at LBNL, our relationship to other high-energy physics institutions, and our plans for future work

The Berkeley HEP program makes essential contributions in four broad scientific areas: at the energy frontier through the search for the origins of mass; in the quark flavor mixing sector through the search for the mechanisms of CP violation; in the lepton flavor sector through the study of flavor oscillations of reactor and solar neutrinos; and in particle astrophysics through the study of dark matter and dark energy. These flagship science efforts are complemented by theoretical studies, and the activities of the Particle Data Group. AFRD provides a foundation for current and future accelerator programs. The priorities of the Berkeley effort are directly aligned with those of the national program.

In each of our five major efforts, SNAP, ATLAS, Advanced accelerator physics and technology, BaBar and CDF, we make significant and essential contributions. In addition, we lead the Particle Data Group, development of optical particle accelerators, the US KamLAND collaboration, oversee R&D for future neutrino factories, and participate in Linear Collider (LC) R&D. LBNL's historical role has been one of physics from 'start to finish'. We participate in the conception, design, construction, commissioning, operation, physics analysis and preparation of upgrades in our experiments. The support and facilities of the Laboratory allow us to carry these roles very effectively in a way not possible even in large university groups.

The future program at Berkeley can be reliably extrapolated from the natural development of the ongoing activities. Our physics program will increasingly focus on discovery of the origins of mass, and on determining the nature of the Dark Energy. SNAP and ATLAS have become the largest components of the Physics Division program. In AFRD the superconducting magnet program (including the National Conductor Development Program) and the accelerator physics and instrumentation programs will be supplemented with the LHC Accelerator Research Program (LHC-ARP). Neutrino experiments will be a joint effort with the Lab's Physics, Nuclear Science and Accelerator divisions. R&D efforts for both instrumentation and computing will be ongoing. We anticipate technical contributions to the development of the Linear Collider physics case as the next major element of the International Accelerator Program. The Linear Collider accelerator efforts will grow commensurate with the national linear collider collaboration.

Berkeley has helped to shape high-energy physics in the US over the past decades and is making crucial contributions to the program today. This record of innovative and outstanding performance highlights our scientific achievements.

1 LBNL Role in U.S. HEP program

The goal of the LBNL HEP effort is to advance and support the U.S. HEP program through the maximum usage of the unique capabilities available in a large national laboratory closely tied to a major university. LBNL staff and U.C. Berkeley faculty work closely together utilizing the excellent experimental laboratory facilities, engineering and fabrication facilities and state-of-the-art computing resources available at the Laboratory and the large number of excellent graduate and undergraduate students who are part of the University.

Major HEP experiments require the fabrication and operation of complex particle detectors and the manipulation of huge sets of data, and LBNL, working in collaboration with numerous universities, is playing a major role in several of these experiments, including SNAP, ATLAS, Barbary and CDF. At the same time, although LBNL does not operate a large HEP accelerator facility, it carries out a substantial accelerator R&D program, and collaborates with HEP accelerator laboratories in the construction of new facilities. LBNL invented the concept and initiated accelerator studies for the asymmetric B factory and collaborated with SLAC and LLNL in building PEP-II, and has been active in support of luminosity upgrades for PEP-II. There is presently a collaboration with Formula, Brookhaven, and CERN in building the high luminosity interaction regions of the LHC, as well as a collaboration on future accelerators including the Linear Collider and potential upgrades of LHC. LBNL is leading the SNAP program to determine the characteristics of the Dark Energy.

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LBNL has played a major role in the development of large detectors for Fermilab, SLAC and the LHC. It was a lead institution bringing the silicon strip vertex detector technology in CDF. This work had a major impact on the top quark discovery, and led to the use of silicon trackers in virtually all collider detectors. LBNL, in collaboration with others, developed several of the crucial readout chips. At the same time it designed and built mechanical systems for both the DIRC particle ID and the SVT silicon systems and was responsible for SVT final assembly and installation. LBNL has taken leadership responsibilities in both the silicon strip system and the extremely challenging pixel system, and is collaborating with many university groups on their construction. LBNL responsibilities include both electronic and mechanical aspects, and again engineering support is playing an essential role.

AFRD, in partnership with the Engineering Division, is utilizing core competencies that have been developed over many years, to further the goals of the DOE/HEP program. In recent years AFRD was responsible for developing the concept of an asymmetric energy collider to investigate the decay of B-mesons, and was responsible for the design, construction, and commissioning of the low-energy ring (LER). Upgrades to the transverse coupled-bunch feedback systems, initially designed by LBNL and operating beyond performance specifications, are being implemented to allow for higher luminosity operations. Together with FNAL and BNL, LBNL has taken responsibility for the design and fabrication of critical components of the interaction regions for the LHC, which must operate at unprecedented beam power. More recently, we have taken on major responsibilities and leadership roles in R&D activities for HEP projects such as the Linear Collider, and the LHC Accelerator Research Program, and we continue to play a leadership role in the management of the Muon Collaboration. AFRD also has involvement in luminosity improvement at the Tevatron Run-II, targeted at improving anti-proton yield into the accumulator ring. LBNL has also made significant investments in laser driven advanced accelerator development and currently operates one of the most powerful short pulse laser systems in the world. Recent results on channel guided laser wakefield acceleration were highlighted as cover story of the September 30, 2004 issue of Nature.

2 Physics Division Programs

2.1 Discovery of the Origin of Mass

Exploration of the origin of mass plays a central role in the LBNL physics program. At the present time, the CDF experiment at the Tevatron forms the center of this program through a program of precision measurements of electroweak parameters. In 2007, the ATLAS experiment at the LHC will become the premier facility for such exploration. Further in the future, the Linear Collider will complement LHC research.

2.1.1 CDF

Members of the CDF group have leadership roles as convenors in four analysis subgroups: jet corrections, Higgs, B-tagging and semi-leptonic B physics. The group has contributed to W and Z cross section measurements and on the Z asymmetry to compare with Standard Model predictions.

An LBNL postdoc has carried out a search for a stable SUSY particle, the stop, with other members of the collaboration. Preliminary results on a mass limit have been shown at HEP Conferences. Also an LBNL PHD student has carried out a study of MSSM Higgs production in Run I. A measurement of the top cross section using silicon-vertex tagging has been submitted to PRL. This is the subject of another LBNL PhD student.

2.1.2 ATLAS

LBNL has been a pioneer in the development of new silicon detector technologies for high-luminosity hadron colliders. The LBNL group is continuing this role and is currently leading the U.S. effort to develop and fabricate silicon pixel detectors for ATLAS. The design of the critical front-end integrated circuits for the ATLAS pixel detector was largely an LBNL responsibility. LBNL also has the major responsibility for the design and fabrication of the pixel thermal and mechanical structure, which has required the development of new concepts. The overall support structure for the pixel system is an LBNL responsibility as is fabrication of about one-third of the active detector elements, modules, and the corresponding mechanical supports.

In addition, LBNL, in collaboration with the University of California (Santa Cruz), has completed fabrication and testing about one-third of the silicon strip detector modules for the central (barrel) region of ATLAS. A sophisticated system has been designed and fabricated at LBNL for testing the large number of integrated circuit wafers for the ATLAS silicon strip detector. This test system has been used at Santa Cruz, CERN, and RAL to cope with the testing of the large volume of integrated circuits that are needed for the ATLAS silicon strip system.

The LBNL group has had a seminal role in understanding the physics signatures at high luminosity hadron colliders. This work began in the 1980's and is continuing now for ATLAS. LBNL has a coordinating role in the development of the ATLAS physics simulation program. This ensures a close tie between the technical aspects of the experiment and the rich physics potential of the LHC.

The software and computing expertise available at LBNL is now being utilized to lead the development of the framework code (ATHENA) that will provide the backbone of the ATLAS software. This work builds on the experience of CDF and BaBar, and takes advantage of the strong team of physicists and computing professionals that has been brought together at LBNL.

2.1.3 Linear Collider (LC)

The Berkeley group has participated in the development of the community consensus in favor of the LC over the past few years. Marco Battaglia has initiated a new R&D effort on silicon detectors for the LC. In addition, we have been active in studies of TPC hardware for application at LC. We have collaborated with nuclear physicists interested in upgrades of the STAR experiment at RHIC in order to form a critical mass of researchers in this area.

2.2 Quark and Lepton Flavor Studies

2.2.1 BaBar

LBNL has played a major role in all aspects of the BaBar experiment beginning with the proposal to use asymmetric beams to make precise measurements of CP-violation in B decays. During the construction phase, LBNL had responsibility for the Silicon Vertex Tagger (SVT), the Detector of Internally Reflected Cherenkov light (DIRC) and the Trigger and Drift Chamber Readout. In addition, LBNL led the original development of code for track reconstruction and was responsible for much of the software framework. Most recently LBNL led the design and implementation of a new computing model which has significantly increased analysis speed and has permitted the collaboration to increase its physics productivity.

The physics analysis effort is stimulated by the large data sample already collected, with more B meson data than CLEO collected in nearly two decades. The present LBNL analysis is focused on the following topics: $\sin 2\beta$, B mixing and tagging; charmless, quasi-two-body B decays, including first evidence of the decay to ϕK^+; form factors in semi-leptonic $B \to Dl\nu$ decay; rare τ decays to $\eta K\nu$, $\eta\pi\nu$; branching fractions for double-charm decays, $B \to \bar{D} - D_s^+$; longer-term studies of nonleptonic decays with second class current suppression, including the first observation of $B \to a_0\pi$; and measurement of the angle alpha in $B \to \rho\pi$ decays.

2.2.2 CDF

At the Tevatron, there remains unique physics to be done in the area of CP violation, CKM matrix element measurements and many measurements of properties of B hadrons. The LBNL group has been heavily involved in the area of B physics analysis for many years, contributing to detection of several B decay modes and to mass and lifetime measurements (including the B_s lifetime). LBNL has also contributed to work towards measurements of B_d mixing and observation of time dependence of mixing. In Run II the LBNL initial physics interest is centered on precision measurements of CKM matrix parameters. The main analysis is a measurement of the hadronic moments of semileptonic decays of charged B mesons which provide constraints on QCD corrections to $|V_{cb}|$. This puts to use the expertise of the group, including detailed knowledge of the hadronic trigger that uses the SVT, and prepares the group for more complex measurements later on. In preparation for B_s mixing studies, the LBNL group has been working on full reconstruction of B_s decays.

2.2.3 KamLAND

The persistence of deficits in solar neutrino experiments and the impressive results from Super Kamiokande on atmospheric neutrinos was the impetus for new, higher sensitivity measurements of neutrino oscillations. The KamLAND experiment exploited the old Kamiokande underground site and the presence in Japan of large nuclear power rectors. The substantial investment ($20M) made by the Japanese government provided a firm basis for the development of this experiment. The LBNL-led US KamLAND Collaboration proposed several initiatives designed to make this experiment robust against potentially crippling backgrounds and to increase its sensitivity still further, enabling it to eventually measure directly solar neutrinos from ^{7}Be.

The one kiloton liquid scintillator target/detector results in approximately 750 neutrino events per year from the reactors, though they are 140 to 200 km away. The very large ratio of this distance to the neutrino energy enables KamLAND to reach two orders of magnitude further in Δm^2 than any previous reactor experiment, making it the first terrestrial experiment to address the solution to the solar neutrino problem. LBNL's contribution to the experiment, in addition to management and oversight (with UCB) centered on specialized waveform capture electronics ideally suited to KamLAND's needs. LBNL is also completing the construction of a new calibration system for the detector, the 4π Arm.

2.3 Dark Energy and Dark Matter

The impact of Berkeley astrophysics programs has been tremendous. The discovery that 95% of the universe is composed of dark matter and dark energy, neither of which is described by our Standard Model, gives a clear focus to the program.

2.3.1 *Supernova Cosmology Project and the Nearby Supernova Factory*

The LBNL Supernova Cosmology Project was the first group to show how distant supernovae could be discovered on a reliable basis and that their brightness and redshift could be properly interpreted to measure fundamental cosmological parameters. Their data gave the first evidence that the geometry and fate of the Universe do not conform to expectations. These astonishing conclusions are the impetus for further studies to reduce systematic errors and to probe more deeply the physics that underlies these phenomena. LBNL scientists are working with other groups to study supernovae at high redshift using ground-based telescopes and the Hubble Space Telescope. At the same time, more low-redshift type Ia supernovae are needed for systematic studies and a broad effort for this is already underway.

The Nearby Supernova Factory *(SNfactory*) has been designed to lay the foundation for current and next generation experiments to determine the properties of Dark Energy. It will discover and obtain lightcurve spectrophotometry (simultaneous broadband lightcurves *and* spectral time series) for more than 300 SNe Ia supernovae in the low-redshift end of the smooth Hubble flow. Their statistical power alone will lower the statistical error of the current SCP results by up to 50% and will help reduce the systematic error. In the longer term, they will improve *SNAP*'s constraint on Ω_M by 40% and on w_0 by a factor of two. The SNfactory is now operating its search pipeline using the Quest camera on Mt. Palomar and it has commissioned a new spectrograph (SNIFS) on the University of Hawaii 2.2 m telescope.

2.3.2 SNAP/JDEM

With a 2m telescope and 600-million pixel imager, SNAP (Supernova/Acceleration Probe) could discover and obtain high-signal-to-noise calibrated light-curves and spectra for over 2000 Type Ia supernovae at redshifts between z = 0.1 and 1.7. This would help eliminate possible alternative explanations, give experimental measurements of several other cosmological parameters, and put strong constraints on possible cosmological models. The imager would use the CCD developed by the Physics Division. These CCD's have a high resistivity substrate with excellent quantum efficiency at long wavelengths. Their development was a direct spin-off of previous investments in SSC detector technology.

For the past 4 years, LBNL has carried out a broad program of R&D to define the science case for SNAP and to develop the technologies needed to realize the program. In November 2003, NASA and DOE announced a Joint Dark Energy Mission (JDEM) for which the SNAP collaboration will compete. LBNL scientists are members of the Science Definition Team for JDEM. As this team begins its deliberation, the plan and schedule for these studies will become more clear.

2.3.3 Cosmic Microwave Background

The Physics Division has set new long term goals for the CMB program, which will cumulate in a precise characterization of the CMB polarization. This will provide insight on the early phase of inflation—a key element in the puzzle of understanding dark energy. A diverse team of innovators has been assembled to address these challenges, in a partnership with UCB campus and NERSC. LBNL's flagship CMB polarization experiment is POLARBEAR, which is a ground-based CMB observatory to be built in two stages over the next 3-5 years. POLARBEAR has the potential to probe GUT scale energies of 10^{16} GeV, by detecting the fingerprint that inflationary gravity waves (IGW) leave on the curl-component of the polarization. It will make precision measurements of the polarization signal down to angular scales of an arcminute, allowing it to precisely measure the cosmic shear signature. Cosmic shear carries information about the matter distribution and neutrino masses—and must be well understood to measure the IGW signal. On the road to these discoveries, LBNL is developing the instrumentation to be used in POLARBEAR through participation in two key NSF-supported CMB experiments being constructed to perform large scale surveys of galaxy clusters with the Sunyaev-Zeldovich (SZ) effect, APEX-SZ (2004) and the South Pole Telescope (2006). Galaxy clusters can be used as test masses to trace the expansion history of the universe, allowing for independent confirmation of the SN1a acceleration results using a different technique with different systematics.

Complementing these instrumentation advances is a vigorous theory and data analysis effort. Currently it is focusing on the analysis of MAXIPOL (the polarization sensitive successor to MAXIMA) data and the development of algorithms for the analysis of the Planck satellite data. The new science and the large data sets expected from APEX-SZ, and POLARBEAR will require an expansion of our theory effort.

2.4 Theory

The Particle Theory Group, including its LBNL and Berkeley campus components, is one of the world's leading research groups and an important center for the training of students and postdoctoral fellows. The traditional coherence of theoretical research with the experimental program of the Physics Division is a special strength of the LBNL group. Research is carried out in the Theory Group over a very broad range of subjects, ranging from M-theory to phenomenological studies of immediate importance to experiments, especially ATLAS and BaBar. Recent work by Berkeley theorists and their collaborators on the possibility that there are extra macroscopic dimensions has inspired a profusion of new investigations throughout the field.

2.5 Particle Data Group

The Particle Data Group provides essential up-to-date summaries of experimental and theoretical particle physics to the HEP community and other physicists and to teachers and students. LBNL is the headquarters of a large international effort to provide compiled and evaluated information on particle properties and related areas, as well as reviews, tables, plots, and formulae. The PDG consults with over 700 physicists from every major particle physics institution in the world to obtain expertise on data and specialized topics, and to insure that the summaries reflect the current viewpoints of the community. An international advisory committee reviews all publications and operations annually. The information is made available through the biennial publication of the "Review of Particle Physics" (an 800-page book), and the "Particle Physics Booklet."

The Particle Data Group has a large impact in science education and awareness. The "Review" and "Booklet" are used by thousands of students and teachers. The PDG collaborates on several educational projects including the QuarkNet program, the Contemporary Physics Education Project, the award-winning "Particle Adventure" website, the CDROM-based exhibition version, the "Quark Adventure," and the Nobel Foundation's Nobel Electronic Museum. These projects make particle physics accessible to non-scientists and enable high school and college teachers to use particle physics in introductory physics courses.

3 AFRD Programs Relevant to Particle Physics

The Accelerator and Fusion Research Division together with the Engineering Division, has developed a set of core competencies that have made significant contributions to existing HEP facilities, and that continue to make contributions to both the near term, and longer term national programs in particle physics. These activities are supported by the DOE through base-programs (resident in the AFRD Center for Beam Physics and the Superconducting Magnet Program), and through collaborative efforts associated with the US/LHC program, the LC collaboration, the Tevatron Run-II and the Neutrino Factory/Muon Collider collaboration. Areas of core competency include: accelerator lattice design coupled with beam dynamics theory and simulation'; advanced accelerator modeling, and accelerator commissioning; diagnostics; beam control and fast-feedback; vacuum technology; beam/laser/plasma studies, both theoretical and experimental, and ultra-high peak power laser technology; RF cavity design, fabrication, and testing; superconducting magnet design and technology development; superconductor material, wire, and cable development; induction linac; and ion source and RFQ development (including intense H^+ and H^- sources).

These skills have been brought to bear in significant contributions to the Advanced Light Source (entirely designed, built, and commissioned by an LBNL team), the PEP-II B-Factory, the E157 experiment at SLAC, the LC, MICE, Tevatron, Neutrino Factory, and VLHC studies, and – in the case of ion sources and RFQs – to many of the operating HEP and Nuclear Physics facilities around the world.

It is worthy of note that the “national laboratory” environment, with its wealth of inter-disciplinary intellectual expertise, access to students and postdoctoral fellows, and technical infrastructure and facilities, is an ideal place to nurture and develop the skills necessary to support future HEP endeavors. Indeed, LBNL strives to be the “partner of choice” in the development, design, construction, and operation of the next generation of accelerators for high energy physics.

3.1 Current Activities

Coming hot on the heels of the spectacularly successful involvement with the PEP-II B-Factory construction and commissioning, AFRD physicists, along with the Lab’s Engineering Division, are now active in many aspects of the national HEP program. In particular, we are building components and designing diagnostics for the LHC, we lead the nation’s research in the development of very high field accelerator magnets in the Superconducting Magnet Program, and in the Center for Beam Physics we have taken responsibility for the damping ring systems for the LC, we provide the top management for the muon/neutrino collaboration, we provide accelerator physics support for the Tevatron Run-II, leadership in advanced computer modeling of accelerators and we are exploiting our world class capabilities in laser driven acceleration and laser-plasma interactions in general – both theory and experiment. The following sections outline in more detail our current work in these areas.

3.1.1 The Large Hadron Collider

LBNL is making critical contributions to the LHC accelerator systems as part of the US/LHC Collaboration, in partnership with BNL and FNAL. The LBNL contributions include the design of the coil packages and supply of NbTi cable for the interaction region quadrupoles (currently being fabricated at FNAL), and an ongoing investigation of the electron cloud instability – an effect that has the potential to deposit unacceptable amounts of thermal energy into the cryogenic system. Our current efforts are centered around the design and fabrication of eight technically challenging cryogenic feed boxes for the interaction regions, and on the beam collimators and neutral beam dumps that are critical to the protection of the interaction region quadrupoles from excessive radiation. We have also developed and tested a novel idea that will transform the otherwise passive beam absorbers into an active on-line bunch-by-bunch luminosity monitor.

3.1.2 The Superconducting Magnet Program

The AFRD Supercon Program, recently lauded as “the jewel in the crown of the national high-field magnet program” by DOE reviewers, has two main thrusts. (1) To collaborate with industry, university groups, and other national laboratories in the development of superconducting materials, wire, and cable necessary to push accelerator magnets to ever higher fields. (2) To make innovative technological advances in very-high field magnets (design and fabrication) that can be transferred to full-scale accelerator quality systems.

The first of these endeavors is embodied in the DOE/HEP National Conductor Development Program, a \$500K per year effort administered through Supercon. The demanding goals are to develop conductor that can reach a superconductor current density of 3000 A/mm^2 (at 4.2 K and 12 T), at a net cost of \$1.5 per kA-m (i.e., the cost of NbTi superconductor at the time of the SSC).

Now in the sixth year, the program has made impressive progress towards these goals, with Nb_3Sn conductor exceeding 3000 A/mm^2, and prospects for the cost goals to be met when the processes, now at the research stage, are properly industrialized. Emphasis of the program is now turned toward reducing filament diameter while maintaining the current density.

The route to very-high field accelerator magnets is being pursued through parallel research paths, including sub-scale magnets for technology development and a variety of large magnets that probe the ultimate performance limits. This approach resulted in efficient use of the program resources and led to successful tests of three record-field dipoles based on three different coil configurations: cosθ (D20, 13.5 T); common coil (RD3b, 14.5 T); block-coil (HD1, 16.1 T).

While we develop the enabling technology base for future high-energy colliders, we are also well positioned to provide significant contributions to HEP in the near term. In particular, LBNL is a key player in the US LHC Accelerator Research Program (LARP). Started in 2003 by the U.S. Department of Energy, LARP is a collaboration of BNL, FNAL and LBNL directed toward the development of advanced magnet technology for future LHC upgrades. LBNL supports this program with a broad effort involving design studies, Nb_3Sn conductor R&D, mechanical models, and simple prototypes. The HEPAP committee has determined that such a luminosity upgrade is "absolutely central" to the future of HEP. In addition, we are providing support to ongoing projects (separately funded) in other areas of science, such as nuclear physics, fusion energy science, high energy density physics, light sources, and nuclear magnetic resonance.

3.1.3 The Linear Collider

The path towards realizing the Linear Collider is being pursued in partnership with a number of institutions worldwide, notably SLAC, FNAL and Cornell in the US, KEK in Japan, and LNF and DESY in Europe. Within AFRD we have a leading role in studies for the damping ring complexes for both the electron accelerator and the positron accelerator. This effort includes detailed lattice design work that addresses the challenging specifications for these unconventional, state-of-the-art storage rings. We are investigating a range of beam dynamics issues that threaten to limit the beam quality in the damping rings; generation of highly stable, ultra-low emittance beams will be essential for operation of the upstream systems and the production of luminosity. Of particular concern are dynamic acceptance limitations from the long damping wigglers; achieving the very small vertical emittance goal in the presence of alignment and tuning errors; and collective instabilities associated with the relatively high bunch charge, including space-charge effects and the fast-ion instability. In addition to the dynamics studies, we are assessing component requirements leading to detailed specifications for the various accelerator systems, including the injection and extraction kickers, the vacuum and RF systems, and the damping wigglers. This work builds directly on the core competencies developed from our experiences in the construction, commissioning and operation of the ALS and the PEP-II Low Energy Ring. Collaborative experimental studies are being pursued with our accelerator physics colleagues at the ALS, and at the KEK Accelerator Test Facility in Japan. Particular topics for study are tuning techniques for achieving the specified vertical emittance, and the detailed dynamical effects of wigglers.

3.1.4 The Muon/Neutrino Collaboration

LBNL has taken the lead responsibilities for the US Neutrino Factory and Muon Collider Collaboration through providing the collaboration spokesperson and the R&D manager. These are significant tasks for the collaboration, especially since the collaboration has increased to include more than 140 members from over 30 institutions – and these numbers are growing! LBNL also provides three members of the collaboration Executive Board, and four members of the Technical Board. Technically the program has been divided into six major R&D areas: beam simulations, a beam cooling experiment known as MUCOOL, targetry, acceleration/storage ring physics, the proton driver, and beam phase-rotation. The immediate goal of the collaboration is to develop a "ZDR-level" understanding of a Neutrino Factory in about three years, leading to a conceptual design two years later. Within AFRD we are contributing to: the beam simulation and theory effort, and have completed a full front-end study; the MUCOOL experiment – through design and testing of the novel 201 MHz and 805 MHz RF systems, and the large-aperture superconducting solenoid magnet system, soon to be tested at FNAL; an the design of the induction linac system for phase rotation.

LBNL is also taking a substantial role in the Muon Ionization Cooling Experiment (MICE). We provide the Deputy Spokesperson for the MICE Collaboration and the WBS Level 2 manager for the RF-Coupling Coil (RFCC) module, as well as membership of the MICE Executive Board and MICE Technical Board, and the MICE Collaboration Board.

3.1.5 Laser driven accelerator program

The l'OASIS Group in AFRD studies, experimentally and theoretically, the interaction of high intensity lasers with particle beams and plasmas. The immediate goal is to develop very high gradient (10-100 GV/m) acceleration of electron beams with significant charge (~1 nC/pulse), and emittances comparable to, or better than, modern RF photo-cathode sources. Recently, two key milestones of a future laser driven accelerator have been achieved using the L'OASIS multi-beam, multi-terawatt laser system: (1) laser guiding at relativistic intensities using preformed plasma channels and (2) the production of high quality electron beams with a few % energy spread at 100 MeV level, containing in excess of 0.3 nC per bunch. The normalized emittance was found to be below 2 π mm-mrad. These experiments have demonstrated several important elements: preformed plasma channels can be tuned to guide ultra-high intensity lasers over 5-10 Rayleigh ranges. At laser power levels on the order of 4-5 TW, guiding of the laser pulse was achieved without production of trapped electron beams or dark current. By tuning the plasma channel conditions, electron beams with low energy spread were obtained when the acceleration distance was matched to the electron dephasing distance. These results were chosen as cover story for the September 30th 2004 issue of Nature.

Two new experiments are underway. The first experiment aims at demonstrating laser triggered trapping and the second at obtaining GeV electron beams for a laser accelerator. These will be discussed more in detail in Section 5.2. The theory and simulation effort in the group has developed analytic and computational tools to understand the results of the experiments. These tools are also being used to develop new concepts. . The program has been augmented through strong collaboration with the University of Colorado, Boulder and Tech-X corporation and with the University of Nevada, Reno (UNR) for developing Particle-in-Cell simulation codes, as well as through collaborations on experiments with UNR and Oxford University (UK).

Thanks to substantial investments in l'OASIS by DOE/SC/BER a 100 TW class, 10Hz solid state laser has been installed and is undergoing final commissioning. The new experimental area to house this laser system has been made possible by a substantial institutional investment of infrastructure funds.

3.1.6 Accelerator Modeling and Advanced Computing

The Accelerator Modeling and Advanced Computing program, led by R. Ryne, has been established to develop leadership in algorithms and software to enable large-scale simulations on parallel tera-scale (and later peta-scale) computers. The motivation for this effort is driven by the complex 3-D, nonlinear, multi-scale, many-body interactions characteristic of future accelerator design issues. Large-scale simulations can help to guide design choices, for example in elucidating the strong-strong beam-beam interaction to improve luminosity in colliders, in modeling beam-halo formation in high intensity proton drivers to determine technical specifications, and to model extreme conditions like those found in laser/beam/plasma interactions. The AMAC program has established strong and productive ties with other programs within AFRD as well as with the ALS Division and NERSC.

3.1.7 Tevatron Run-II

LBNL participation in the task of optimizing the luminosity of the Tevatron complex has led the study of aperture limitations in the AP2 transfer line that connects the anti-proton target to the Debuncher ring. The Run II Luminosity Upgrade plan calls for increasing the transmission of the line from the observed 20 pi mm-mrad to 40 pi mm-mrad. Earlier attempts to do so were unsuccessful and LBNL was asked to develop an understanding of the line and propose ways to improve it. In addition, we anticipate identifying and developing specific diagnostic instrumentation that can aid in the commissioning process

4 Future Directions for the Physics Division Program

The future program at Berkeley can be reliably extrapolated from the natural development of the ongoing activities. Our physics future will increasingly focus on discovery of the origins of mass, and on determining the nature of the Dark Energy. SNAP and ATLAS have become the largest components of the Physics Division program. We plan to maintain the diversity of our program with a complementary effort in neutrino physics, which will be a joint effort with the Nuclear Science Division. R&D efforts for both instrumentation and computing will be ongoing. The Linear Collider efforts will grow commensurate with the national linear collider collaboration.

The Physics Division Strategic Plan describes the planning assumptions and our future plans. The assumptions we made for planning purposes are shown in Figure 1. Key dates and elements of the LBNL program are shown in Figure 2. We have already made significant adjustments in resources to match these priorities.

In the Physics Division the accelerator-based efforts can be mounted in scenarios with modest budget increases. However, an increased involvement in LC, additional efforts in neutrinos, or effort on other large new accelerator-based projects would require a restoration of buying power to the Division's budgets. For the particle cosmology program, additional funding will be required. R&D support of future efforts, both accelerator-based and non-accelerator-based, should be restored in parallel with strengthening the existing efforts in an increased buying power scenario. Our traditional contributions to the community should be maintained. In the following sections, we provide more details on each of the elements of our future HEP program.

4.1 Dark Energy, Dark Matter and Cosmology

Recent studies of high redshift type Ia supernovae (SNe) observed with the Hubble Space Telescope (HST) and ground-based telescopes confirm the Supernova Cosmology Project's (SCP) well known 1998 result, which, based on a sample 42 type Ia supernovae, excludes a simple Ω_M =1 flat universe and presents strong evidence for the existence of a cosmological constant (Ω_Λ>0). To fully exploit the use of SNe Ia as cosmological probes and to study the "dark energy" that is causing the acceleration of the universe's expansion, a space-based telescope such as SNAP is needed. The conceptual design and requisite R&D for such a space mission form a large part of our program. For continued studies of SN Ia cosmology while SNAP is being prepared, the SCP will continue its program of supernova search/identification/and follow-up campaigns in the mid- to high-redshift region employing coordinated multi-epoch observations using the most powerful ground-based telescopes and the Hubble Space Telescope (HST). However, these high redshift studies will be completely dominated by known and potential systematics unless SNe Ia are better calibrated and scrutinized far more closely for (as yet undetected) systematic effects and towards this end we are developing the Nearby Supernova Factory (SN Factory) which will provide a major improvement on the low-z end of the Hubble diagram (0.03 < z < 0.08) by providing a substantial increase in statistics and greatly improved control of systematics.

4.1.1 Supernova Cosmology Project and the Nearby Supernova Factory

The goals of SCP program are to add statistics to the middle region of the Hubble diagram (.3 < z < .8) and extend it to z > 1. Prior to SNAP, such studies can provide a measurement of the dark energy equation of state, $<w>$ (time average) that is limited in precision, but may still be able to distinguish a cosmological constant (w = –1) from alternative models. The SCP is collaborating with a major five-year legacy survey using the Canada-France-Hawaii Telescope that will yield hundreds of SNe Ia in the mid-redshift range.

A second focus of the current program is to use HST to study SNe with z > 1. Though the statistics of these very high SNe will necessarily be small due to the limited field of view of the HST, such events will be of great interest as they allow us to look back to the acceleration/ deceleration transition era.

The Nearby Supernova Factory *(SNfactory)* is designed to lay the foundation for current and next generation experiments to determine the properties of Dark Energy. It will discover and obtain lightcurve spectrophotometry (simultaneous broadband lightcurves *and* spectral time series) for more than 300 SNe Ia supernovae in the low-redshift end of the smooth Hubble flow. Their statistical power alone will lower the statistical error of the current SCP results by up to 50% and will help reduce the systematic error. In the longer term, they will improve SNAP's constraint on Ω_M by 40% and on w_0 by a factor of two. This SNe dataset will further serve as the premier source of calibration for the SN Ia width-brightness relation and the intrinsic SN Ia colors used for correction of extinction by dust (needed by SCP and SNAP). This dataset will also allow an extensive search for additional parameters, which influence the quality of SNe Ia as cosmological probes. Well-observed nearby SNe Ia, especially in host galaxies spanning a wide range in star-formation histories, are essential for testing for possible systematics. Following the successful commissioning of SNIFS in late 2004, the project is ready to carry out its program of supernova studies.

Measurements of the CMB will complement the studies of supernovae and provide crucial data on dark energy and dark matter. LBL is in a unique position to take a leadership role in the development of instrumentation for the next generation of CMB observations. Having characterized the CMB temperature anisotropy, CMB science is taking the next observational step by measuring the polarization anisotropy and small angular scale CMB secondary effects, such as the Sunyaev Zel'dovich effect and cosmic shear. These measurements have the potential to provide insights into the expansion history of the universe that are perhaps even more exciting and ground breaking than the revolutionary insights provided by the temperature anisotropy.

4.1.2 SNAP

In November 2003, NASA and DOE announced an agreement to fund a Joint Dark Energy Mission (JDEM) with a competitive process to select a mission in 2006. This decision has significantly changed the course of the SNAP program at LBNL and within the collaboration. NASA and DOE have formed a Science Definition Team and LBNL will be very active in that effort. Three LBNL scientists from SNAP are on the team and they will be supported by the simulation efforts within the SNAP collaboration. In addition, the SNAP detector R&D effort is now critically important.

The SNAP science hinges on the reach to high redshift supernovae and precision weak lensing measurement only achievable in space. Realization of the science requires state-of-the-art photodetectors in the visible to near infrared (NIR) wavelengths (0.35 – 1.7 μm). A DOE review noted that this is "the most ambitious detector focal plane ever proposed, for ground or space." With the investments we are making in the R&D period, we can advance these devices into the enabling technologies required for the SNAP science program. If we fail to ready these technologies in time, the science reach of SNAP will be reduced and its ability to successfully compete for JDEM will be compromised. The recent technical review in Nov. 2003 by outside experts emphasized this point: "With the recent re-direction to JDEM, it is very important to re-focus and heavily emphasize work on advancing key technologies. Detectors and electronics are likely *the* highest risk area in the mission concept. The visible arrays, and especially the near-IR arrays, are not in the bag." To set the scale of this ambitious program, the IR system that we are proposing contains more devices than are currently deployed on ground-based systems. We realize that serious failure in the R&D program would result in significant loss of science or worse. Likely we would have to consider a much smaller focal plane with the potential elimination of wavebands (visible or infrared) and loss of the dark energy science of greatest interest.

The SNAP team has continued to refine and focus the R&D program. Instead of a Conceptual Design Report for a CD1 review conducted by DOE, our efforts are now focused on developing the science, the technologies, and the concepts in time for the JDEM Announcement of Opportunity, to be issued and competed by DOE and NASA. The overall scope of the R&D program has been refined to take into account the process by putting enhanced effort into simulations to understand various mission concept trade-offs. These studies will be key inputs to the JDEM Science Definition Team. We are carrying out an optimization across the total scientific mission, including the telescope, focal plane, and science simulation to establish scientifically driven requirements. This integrated approach to Dark Energy science is the focus for the SNAP R&D period.

4.1.3 Cosmic Microwave Background

CMB observations have moved from relatively small experiments using a few noise limited sensors to a precision science program employing large sensor arrays to provide the required sensitivity. LBL is already taking a leadership role in the development of instrumentation for the next generation of CMB observations. CMB science is taking the next observational step by measuring the polarization anisotropy and small angular scale CMB secondary effects, such as the Sunyaev-Zel'dovich effect and cosmic shear. The CMB effort can be split into two categories: instrumentation and theory plus data analysis.

The primary focus for the current stage is instrumentation for experiments with large format bolometer arrays. APEX-SZ and the South Pole Telescope will utilize the Sunyaev-Zel'dovich (SZ) effect to search for distant galaxy clusters. The distribution of galaxy clusters vs. redshift is sensitively dependent on Ω_M, Ω_Λ, and *w*. Unlike x-ray or optical surveys, the magnitude of the SZ signal is independent of redshift, so it is well-suited for deep searches. These experiments are complementary to SNAP as they attack the same physics with a completely different technique. The flagship LBL-led experiment, POLARBEAR, aims at detecting gravity waves generated by inflation, which could manifest themselves as a net curl in the polarization field of the CMB (commonly referred to as B-modes). CMB polarization is the only probe known to be sensitive to this inflationary fingerprint.

The instrumentation developments for POLARBEAR are stepping stones towards the technology that will ultimately (post-SNAP timescale) be deployed on a CMB satellite mission, which is foreseen as one of NASA's Einstein probes. Our team includes a co-Investigator and three collaborators on a NASA proposal to develop a CMB polarization mission. Participation in this mission is a natural progression for both SNAP and CMB personnel on a timeframe beyond 2009.

The second category for the CMB effort is data analysis and CMB phenomenology, for which the physics division has nurtured a successful partnership with NERSC. This effort is growing, with LBNL playing an important role in the analysis of MAXIPOL (the successor to MAXIMA) data and in preparing algorithms for the ESA Max Planck Surveyor satellite mission, APEX-SZ, and POLARBEAR. The future for CMB polarization may well be a satellite mission, on a timeframe that follows SNAP. LBNL is positioning itself to play an important role in the design and data analysis of a future CMB polarization satellite.

4.2 Discovery of the Origins of Mass

4.2.1 ATLAS and LHC-ARP

The ATLAS collaboration has started to plan for the pre-operation, operations and research phase of ATLAS. The LBNL construction responsibilities for the silicon strip detector are complete. It is planned to assemble the overall pixel system at CERN starting at the end of 2005. Thus a major part of the LBNL ATLAS work will shift to CERN from early 2005 through 2006 in order to assemble, install, commission and first operate those parts of the ATLAS detector that are LBNL responsibilities. Beyond 2007, LBNL will be required to assume operations and maintenance responsibilities for aspects of the pixel detectors. This will require the continued involvement of technical personnel in both the mechanical and electronics aspects of these detectors, in addition to physicists. A continuous presence at CERN by LBNL personnel will be necessary to fulfill these responsibilities. Similarly, support of the initial operations of the framework code and other software developed at LBNL will be critical to the success of ATLAS in its first years of operation. LBNL computing professionals will be needed to provide this support and are resident now at CERN.

The number of physicists at LBNL involved in the ATLAS will continue to grow. We anticipate a modest growth in the number of faculty and senior physicists but a more substantial growth in the number of postdoctoral physicists and graduate students.

Although completion of the ATLAS detector is still some years away, concepts for upgrades are already under discussion. A major area for potential upgrades is in the tracking detector. The ATLAS design allows the silicon pixel detector to be removed and installed without disturbing substantially the remainder of the tracking detector. One can already foresee the desirability of improvements (e.g. finer granularity, improved radiation hardness, lower mass) to the pixel detector, and R&D to this end should begin already in 2005 if one is to be ready to install improved detector elements after the first few years of ATLAS operation.

4.2.2 Linear Collider

We expect the Linear Collider will be the next International Accelerator Facility to be built. Our efforts on silicon detectors and Time Projection Chambers will continue and will grow as effort on BaBar winds down. Berkeley will make both physics and technical contributions to this facility where we have key technologies to offer.

4.2.3 CDF

The effort on CDF will decrease substantially as part of the Physics Division strategy to move resources to ATLAS. Postdocs will not be replaced as they reach the end of their appointments. The group, however, will maintain a reduced program at Fermilab through 2007. Studies of top quark properties will continue. The group has heavily contributed to the development and optimization of the b-tagging algorithm. The group has concentrated on analyses that use b-tagging. Work on the top mass measurement, using events with a tagged b jet, will continue. A new method for determining the top mass is being developed by an LBNL postdoc, with contributions from other members of the group. The aim is to reduce the statistical error by using a novel likelihood procedure.

4.3 Quark and Lepton Flavor Studies

4.3.1 BaBar

The LBNL BaBar Group will continue to be active in the experiment until 2008. The group will continue to work on a number of analysis topics. There are great opportunities at BaBar with the prospects for 500 fb^{-1} by the end of 2006. This will permit the collaboration to resolve the discrepencies in sin 2β in different channels, make a high-precision measurement of α, make a measurement of γ with moderate precision, make a precise determination of $|V_{cb}|$ and $|V_{ub}|$, explore the D and D_s and X(3872). It addition, it will be possible to study strong dynamics in weak decays (e.g. B -> VV) and to search for new physics in B-> $X_s ll$.

4.3.2 CDF

We have begun a vigorous program to exploit the physics opportunities in RUN II. The LBNL physics interest is centered on precision measurements of CKM matrix parameters. Observation and measurement of B_s mixing and determination of x_s is a hallmark measurement for CDF. In order to resolve these oscillations at large x_s, the proper decay length of B_s must be determined with high precision. This forces CDF to use fully reconstructed decays for the measurement.

4.3.3 Neutrino Physics

Important upgrades are planned to allow KamLAND to be sensitive to solar neutrinos. Strong support from the US-Japan agreement is anticipated to help carry out this effort. The solar neutrino measurements place stringent demands on backgrounds, requiring purification of the scintillator oil. LBNL's Physics and Nuclear Science Divisions support this effort jointly. Possible construction of a National Underground Laboratory is an important opportunity for neutrino physics in the future. Recently, we have obtained support through LDRD to investigate the possibility of a reactor experiment to measure θ_{13}.

5 Future Directions in AFRD Particle Physics

AFRD programs are well positioned to provide a wide array of critical R&D activities of central relevance to the national program in particle physics. We have a highly talented team of scientists and engineers who have developed an impressive arsenal of skills and tools. In the immediate future our experts in beam electrodynamics and rf-systems are providing assistance to Fermilab in its luminosity improvement efforts. The laser acceleration efforts are expected to result in a unique compact GeV module. When we look to the future, we anticipate taking major responsibilities in the R&D and construction activities associated with large facilities built elsewhere – as we do now within the US/LHC program. We foresee a fruitful collaboration with CERN as part of US support to LHC accelerator commissioning and operations. Berkeley's expertise in computer networking and visualization makes LBNL a natural testbed for a Global Accelerator Network. The main elements of our future program are superconducting magnet development principally aimed at upgrades for the LHC, and in the development of all-optical acceleration techniques and beam diagnostics, towards a 10 GeV laser driven accelerator.

5.1 Supercon

The achievement of 16 Tesla in a dipole configuration is a major step, establishing the feasibility of Nb_3Sn for accelerator applications. Achieving the ultimate goal of producing an industrialized, multi-meter length magnet with large aperture and accelerator field quality will require an intensive, long-term effort that will be a combination of LARP and the LBNL base program.

The near-term goals (5 – 7 years) include increasing the field to the maximum practical limit for Nb_3Sn, which is approximately 17 Tesla, increasing the bore size and improving the field quality. Length issues are particularly important to understand, and within the next 4 – 5 years, a quadrupole with a length of over 3 meters should be produced, followed a few years later with the demonstration of a practical quadrupole that meets the requirements for an LHC interaction region upgrade. A very high field collider dipole that can operate under high synchrotron radiation heat loads will take significantly longer to develop. With a vigorous, adequately-funded program, a demonstration of this technology can be achieved by 2015.

The main component of the magnet program in FY06 will be the fabrication and test of HD2. A successful test of HD2 will represent a promising step toward an LHC energy doubler (~15 Tesla operating field); in particular, for upgrade scenarios involving a high field, single-turn injector with a limited dynamic range in the main collider ring.

The magnet design and analysis effort in FY06 will be directed towards a further increase of the dipole field. This objective will require a combination of improved material properties, better design efficiency, and a complete understanding of the behavior of the coil and structure under large forces. As a next step in this direction, an upgraded version of HD1 will be developed, aiming at a dipole field above 17 T. This goal may be achieved using the fabrication and testing experience from HD1, improved conductor, and a lower operating temperature.

The sub-scale program will continue with investigations into conductor and insulation development, new instrumentation, thermo-mechanical effects and quench protection studies. In addition, the fabrication and test of a sub-scale coil using High Temperature Bi-2212 conductor will be pursued, in view of possible applications of HTS technology to develop coil inserts for the main dipoles.

Several issues will need to be addressed to further advance our high-field magnet technology towards its application in future high-energy accelerators. Following HD2, we will begin the design of HD3, a demonstration dipole suitable for an LHC doubler. . The objectives for this magnet are to achieve a short sample dipole field of 17 Tesla (using graded coils with either Nb_3Sn or HTS inserts), a 40-50 mm aperture, to expand the options available to the accelerator designers, and improved field quality.

5.2 Center for Beam Physics

CBP staff continue to provide leadership in accelerator physics in support of HEP accelerator-based facilities. Experimental work, theory, and computational modeling provide a broad base of expertise applicable to solving a multitude of problems for the DOE HEP program. In addition to developing involvement in operational HEP facilities (PEP-II and Tevatron), activities in support of future facilities (LHC, ILC, neutrino factory/muon collider, superconducting module and test facility (SMTF)) are ongoing.

5.3 L'Oasis

The l'OASIS Program on Laser Driven Accelerators is focused on the development of laser based physics and technology for advanced accelerators and fundamental laser-matter interaction physics. In the next decade, research will continue on the development of a laser driven electron accelerator. These efforts will initially be centered around the l'OASIS facility that houses a multi-million dollar state-of-the-art Ti:sapphire based laser system with up to 6 beam lines, shielded target areas with currently two target chamber and a remote control room. This facility is unique in the USA. In the second phase, a dedicated user-style facility is envisioned that can support several external users at the same time and provide laser beam time in a similar fashion to existing "Large Scale European Facilities" such as at the VULCAN laser at Rutherford Appleton Laboratory (UK) and the LULI2000 laser at the Ecole Polytechnique (France). LBNL would be a node in a National Network of such facilities as was proposed in the SAUUL report.

The L'OASIS program will continue to build on the skills and unique expertise that has been developed at LBNL on designing, building and operating ultra-high peak power, high repetition rate laser systems for experiments involving the following components:

1. 1 GeV laser module: Recently it was successfully demonstrated that a laser can propagate over many diffraction distances using preformed plasma channels that serve as optical fibers for guiding the intense laser beams. It was demonstrated that 100 MeV beams can be produced using 10 TW class laser pulses that are guided over 2-3 mm. The goal for the next few years is to demonstrate guiding of 100 TW class beams over 5-10 cm distance which should result in the production of 1 GeV-class electron beams.
2. Laser triggered injection: Methods will be explored to control the injection timing and, hence, the energy spread of electron beams into plasma based structures. These methods will allow the production of narrow energy spread electron beams with state-of-the-art emittance and bunch durations below 10 fs, containing 10's of pC of charge.
3. 10 GeV laser module: Following the development of a 1 GeV module, research will be carried out on the physics and technology of staging several laser driven accelerators together to achieve energy gains of 10 GeV in a distance less than a few meters.
4. Polarized electron beam source: An essential aspect of an HEP relevant accelerator will be to demonstrate the feasibility of a plasma based polarized electron source. Experiments will be conducted to demonstrate that by carefully populating the proper excited states in hydrogen and then ionizing the gas and exciting a plasma wave, to show that polarized electrons can be produced and subsequently accelerated to serve as an injector.
5. Positron production: Another essential element in the development of a laser based accelerator system for collider related physics will be to develop methods of producing and accelerating positrons that are compatible with laser accelerators. This will be studied after successful demonstration of the 10 GeV electron accelerator and will utilize this technology.

6 Conclusion

LBNL has helped to shape high energy physics in the US over the past decades. It has transformed hadron collider physics with the SVX at Fermilab, proposed building an asymmetric electron-positron collider, and then was a major partner in the PEP-II construction and in the design and construction of BaBar, led the development of smart pixel technology for the LHC, and opened the field of supernova cosmology. It has also become a world leader in superconducting magnet technology and in laser driven advanced accelerator research with a state-of-the-art laser facility. This record of innovation and outstanding performance is unique in the U.S. program.